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Depth Separation and Visual Masking

Robert Fox and Stephen Lehmkuhle

Department of Psychology
Vanderbilt University
Nashville, Tennessee 37240

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July 1978

Technical Report

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Virtually all research on inhibitory interactions among adjacent visual stimuli operative in such phenomena as simultaneous contrast and visual masking has employed situations in which the interacting stimulus elements occupy the same depth plane (i.e., have the same z-axis values) in deference to the implicit assumption that the processing of depth information occurs only after the visual processing of contour information is completed. But there are theoretical reasons and data suggesting that the interactions → next

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among contours depends critically upon their relative positions in depth--interactions may not occur if the stimulus elements occupy different depth positions. The extent to which metacontrast masking depends upon depth position was investigated in nine experiments that used stereoscopic contours formed from random-element stereograms as test and mask stimuli. The stereogram generation system permits large variations in depth to be made without introducing confounding changes in proximal stimulation. The main results are: (1) Separation of test and mask stimuli in depth substantially reduces masking; and (2) When more than one stimulus is in visual space, the stimulus that either appears first or appears closer to the observer receives preferential processing by the visual system.

SUMMARY

Virtually all the extensive research on visual masking has used stimuli that lie in the same depth plane (have the same z-axis value), in deference to the implicit assumption that processing of depth information occurs only after the visual processing of contour information is completed. But theory and data are available suggesting that the interaction among contours depends critically upon their relative positions in depth. In nine experiments the role of depth separation on metacontrast masking of target by annulus was examined. To provide a facile method of manipulating depth position that does not introduce confounding variables, stimuli were stereoscopic contours formed from random-element stereograms. The target was a Landolt C whose gap position randomly took one of four equiprobable positions. The mask was an annulus that surrounded the ring. The index of masking was the probability of correct gap location in the Landolt C, using a four-choice forced-choice response. Using practiced observers, a baseline recognition performance was set at 80% correct, at 64-msec exposure duration, for each observer. Initial experiments demonstrated a close parallel between physical-contour and stereoscopic-contour masking--e.g., for zero depth separation and stimulus onset asynchrony (SOA) at zero, recognition performance fell by approximately 40%; masking was an inverse function of the distance between mask and target contours; and masking depended upon configural similarity of mask and target. In the temporal domain, both forward and backward masking were obtained, performance returning to baseline at SOA = 100 msec for backward masking and returning at SOA = -300 msec for forward masking. For depth separation, when the target was in front of the mask, masking declined monotonically as depth separation increased. With mask in front of the target, masking did not decline with increases in depth separation. Supplemental experiments demonstrated that the major results were not due to eye movements nor to changes in perceived size. Together, the results reveal that depth position is a significant factor in contour interaction. Further, there appears to be a positive bias for a stimulus that either appears first in the visual field or occupies the depth position closer to the observer. The implications of these results are discussed.

INTRODUCTION

This paper reports progress on a research project concerned with the effect of depth separation on the interaction between spatially adjacent contours. Interaction refers to the destructive interference that reduces perceptibility--prominent examples are visual masking, simultaneous contrast, and the reduction in recognizability of letter forms embedded in a matrix of competing letters. Virtually all the extensive research on these kinds of interactions have employed stimulus situations in which all contours lie in the same depth plane (have the same z-axis value) and the resulting interactions have been confined to the x and y axes. But suppose the contours were separated in depth. Would destructive interaction still occur? For instance, would a change in disk brightness induced by a brighter surrounding annulus still occur when the disk and annulus appear to lie in different depth planes?

The general theoretical framework that provokes that question and inspires this inquiry consists of two broad alternative approaches to understanding the perception of visual space. One approach has its origins in classic Gestalt psychology, and is represented today by such workers as James J. Gibson (e.g., 1966), Roger Shepard (e.g., 1970), and Fred Attneave (e.g., 1972). Its key assumption is that the relationships among stimuli are encoded, including the relative positions in depth of stimuli in visual space. On this view, information about depth is processed prior to information about specific attributes of the stimuli. In a sense, information about where an object is has priority over information about what an object is.

The alternative theoretical view has its origins with Helmholtz, and has been incorporated in the work of many contemporary investigators. The key assumption is that knowledge about the characteristics or identity of a specific stimulus is constructed from an analysis of specific cues or features of the stimulus. Then, after stimulus identification, information about the position of the stimulus in depth is processed. This view, which might be called specific-feature analysis, in contradistinction to the Gestalt approach, which might be called relational analysis, has been the majority viewpoint. For example, the typical textbook enumeration of specific cues to depth assumes that depth information is processed only after information representing each of the cues has been analyzed and combined.

Moreover, recent theoretical developments in the area of pattern recognition (see, for example, Uttal, 1975; Minsky & Papert, 1969) reflect the specific-feature approach, in that models of pattern recognition deal exclusively with forms lying in the x and y plane without consideration of the process by which information about location of the form on the z axis is obtained. The same bias for specific features is also found in the various models proposed to account for such interactive phenomena as simultaneous contrast and visual masking. The models are restricted to interactions in the x and y plane and require that all contours lie in the same depth plane.

There are, however, some sets of data that suggest that the relative positions of objects in depth play a significant role in determining their perceptibility. Of particular relevance is the program of research on visual space perception initiated by Walter Gogel (for a recent review, see Gogel, 1978). In his efforts to develop a general theory of space perception, Gogel was led to formulate an hypothesis known as the adjacency principle, which states that the degree to which stimulus elements interact to form a stable percept is an inverse function of the apparent distance between them in visual space. A number of tests of the adjacency principle for visual depth separation have been carried out. For example, Gogel and Mershon (1969; also see Mershon, 1972, and Mershon & Gogel, 1970) have shown that the simultaneous contrast demonstration known as the Gelb effect is diminished if test and inducing stimuli appear to lie in different depth planes. Gogel and Kaslow (1971) found that the motion induced in a small spot of light by a larger surrounding framework was eliminated if the spot of light and the framework appeared to lie in different planes of depth. Gogel and Newton (1975) found that the apparent tilt of a vertical rod induced by a surrounding tilted frame (the well known rod and frame illusion) was reduced if the frame and rod appeared to lie in different depth planes. Working within a theoretical framework independent of, yet similar to, Gogel's, Gilchrist (1977) demonstrated that large changes in apparent brightness of a test patch could be produced as a function of the apparent depth plane occupied by the background stimuli on which the test patch appears to be superimposed, even though ambient illumination remains constant.

These results, which showed that changes in apparent depth can alter basic perceptual attributes, clearly favor relational theory and pose special problems for models designed to account for specific interactive phenomena--as, for example, models that employ the hypothesis of lateral inhibition to account for simultaneous contrast. Yet these data, while suggestive, are not completely compelling. In some instances the effects of depth changes have been small, and depth changes have not been systematically manipulated over a broad range of values. A basic reason for this is that it is technically quite difficult to produce apparent changes in depth over a wide range without at the same time introducing substantial confounding differences in proximal stimulation.

An approach that avoids the problem of confounding proximal stimulation while at the same time permitting facile manipulation of large changes in apparent depth is the use of stereoscopic contours generated from random-element stereograms (Julesz, 1971). Such contours do not have identifiable monocular components and arise in the visual system at central stages devoted to stereopsis--in a sense, the contours bypass or skip more peripheral stages. And even though these contours don't exist as physical luminance gradients impinging on the retina, they can induce illusions, aftereffects, and other perceptual phenomena similar to those induced by physical contours. For example, classic figural aftereffects have been demonstrated with stereoscopic contours (Blakemore & Julesz, 1971; Long & Over, 1973; Walker & Kruger, 1972). Visual masking has been found (Uttal, Fitzgerald, & Erskine, 1975; Vernoy, 1976). Moving stereoscopic contours can induce the waterfall illusion or motion aftereffect (Papert, 1964; Lehmkuhle & Fox,

1977) and induce optokinetic nystagmus eye movements (Fox, Lehmkuhle, & Leguire, 1978). Most of the prior research with random-element stereograms have used static or hardcopy displays such as photographs, in which all characteristics of the stereoscopic configuration remain fixed and cannot be modified over time. But quite recent developments in microelectronics have made it possible to continuously generate an almost infinite variety of stereoscopic forms on visual displays and to move the forms about in stereoscopic space without introducing monocular cues.

A system for continuously generating random-element stereograms has been developed at Vanderbilt for various research applications (e.g., Fox, 1978a; Fox, Lehmkuhle, & Bush, 1977; Fox, Lehmkuhle, & Leguire, 1978). The existence of the system and its availability have made it possible to systematically investigate the effects of depth separation on a wide spectrum of perceptual phenomena.

As an initial step in the inquiry, visual masking was selected for investigation. An important reason for selecting masking was that it has been the target of considerable research and many of its characteristics have been well defined empirically. And this effort has been accompanied by the formulation of several explicit theoretical treatments. The literature has been critically reviewed numerous times. For some recent commentary see Breitmeyer and Ganz (1976), Fox (1978b), Lefton (1973), Weisstein (1972), and Weisstein, Ozog, and Szoc (1975). Of the several paradigms that comprise masking, metacontrast has received special attention. In the metacontrast paradigm, the interacting contours (the test and mask stimuli) do not overlap but are in close spatial proximity. For instance, the test stimulus might be a solid disk and the mask stimulus an annulus that surrounds the disk. The relative perceptibility of the disk as a function of the presence or absence of the annulus serves to define the degree of masking.

In the experiments reported here, the metacontrast paradigm was used. Both test and mask stimuli were stereoscopic contours. The test stimulus was a Landolt C with gap position systematically varied and the mask stimulus was an annulus that surrounded the test.

GENERAL METHOD

Throughout the following experiments the same observers performed the psychophysical tasks, the same apparatus generated the stimuli, and in most experiments the same stimuli and procedures were employed. This section covers these common procedural details and includes descriptions of the criteria used to select observers, the electronic system used to generate the random-element stereograms, and the stimuli and psychophysical procedures employed to measure visual masking. The specific procedural details of individual experiments are given in the descriptions of each experiment.

Subjects

Four graduate students served as paid observers in these experiments. Of the four, subjects SLS and SWL were well practiced psychophysical observers and had participated in several earlier experiments using random-element stereograms; subjects CVL and TSL had little experience as psychophysical observers. Subject TSL was naive about the purpose of these experiments.

The subjects were selected according to two criteria, visual test scores and availability. First, in order to complete the psychophysical tasks in a reasonable amount of time, each subject participated for an hour in the morning and in the afternoon, six days per week, for a four-week period. Second, each subject possessed equal and good acuity in each eye (corrected or uncorrected), no lateral phorias, and good stereoacuity. Visual testing was administered on a Bausch-Lomb orthorater, using only the far series of tests.

Apparatus

Each dynamic random-element stereogram, composed of more than 5,000 red and green dots, was projected on a large screen (52 x 69 in) by a projection color television receiver (Advent, model 1000A). The system for generating these stereograms (see Fig. 1) contained two devices built from TTL circuits (i.e., the stereogram generator and the video switching unit) and two video cameras (Panasonic, model WV-240P). This system controlled the size, shape, depth, direction of depth, duration, and position of a cyclopean stimulus. Dichoptic stimulation was accomplished by the anaglyph technique, where observers viewed the projected random-element displays with a red filter (Kodak, Wratten 29) covering the left eye and a green filter (Wratten 58) covering the right eye. In this way, the red dot matrix stimulated only the left eye and the green dot matrix stimulated only the right eye.

The stereogram generator constructed each random-element display by turning on and off the red and green electron guns of the television receiver (the blue electron gun was disabled). The durations of the on and off cycles of the red and green electron guns were precisely controlled as they swept across the face of the screen, which resulted in a sequence of red and green dots; the on and off durations were determined by the

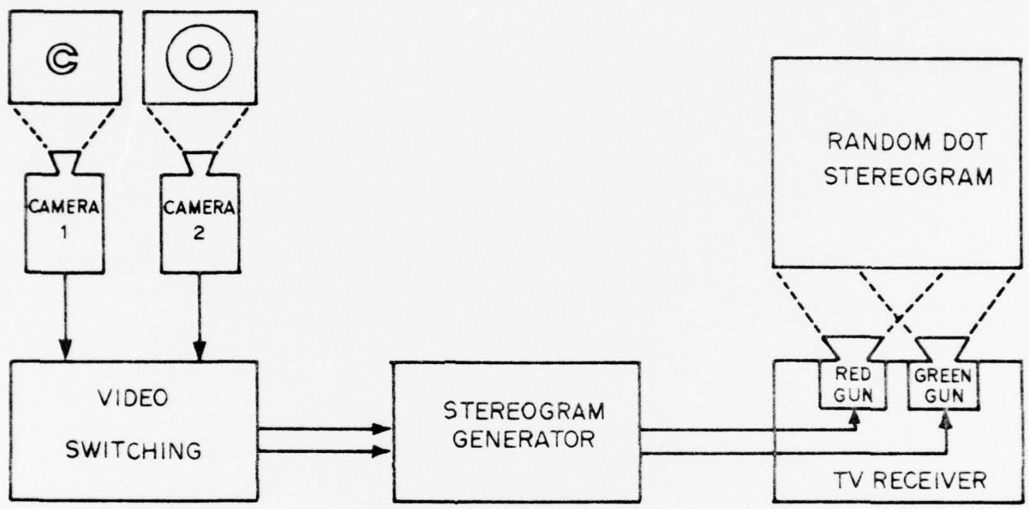

Fig. 1. Block diagram of stereogram generation system.

stereogram generator. Binocular disparity was introduced by delaying the onset of one dot in relation to the onset of its partner dot of the other color, which produced a lateral shift in the positions of corresponding left- and right-eye elements, thereby fulfilling the essential requirements of stereoscopic depth. The area left blank by the shift was randomly filled with dots. The amount of delay between the matrices controlled the amount of disparity. The delay or disparity of the annulus and the Landolt C were manipulated separately. Seven delays were used in these experiments, corresponding to spatial displacements on the projection screen ranging from 0.4 to 2.8 cm in 0.4-cm steps. At a viewing distance of 150 in, these spatial displacements resulted in binocular disparities ranging from 9'9" to $1^{\circ}4'3''$ in 9'9" steps. In all the experiments, only crossed disparities were used. These were produced by displacing the red dots in a temporal direction.

In the random-element displays used in these experiments the position of each dot was changed every 16 msec. The rearrangement of the red and green dots, which made the dots appear to be in continual movement not unlike Brownian motion, was done in such a way as not to alter the relationships between the left and right matrices, and therefore the depth and shape of the cyclopean form was unchanged. The use of such a dynamic display in these masking experiments was essential to remove the nonstereoscopic movement cues that accompany the introduction of cyclopean shapes in static displays.

The stereogram generator alone was capable of producing only rectilinear forms. A more complex form, such as a Landolt C or an annulus, was generated by a video camera acting as an external programming device to control the red and green electron guns. In synchrony with the horizontal and vertical scans of the television receiver, the camera scanned a high-contrast display and emitted an analog video signal that corresponded to the luminance of the display. The stereogram generator decoded the luminance information provided by the camera via a comparator circuit. When the amplitude of the video signal exceeded some predetermined level (in other words, when luminance of the display exceeded a given brightness level), a delay or disparity was introduced between corresponding left-eye and right-eye elements in the random-element stereogram display. When the amplitude was below the critical level, no delay was introduced. As an example, when the camera scanned an achromatic display containing a Landolt C, the stereogram generator decoded the luminance information contained in the amplitude of the video signals and generated the cyclopean counterpart of the Landolt C on the projection screen. In these masking experiments two cameras were used; one viewed the annulus and the other the Landolt C. High-contrast slides of annuli and Landolt Cs were projected by standard Kodak Carousel projectors. These projected images were sufficiently bright and contained enough contrast to adequately program the stereogram generator.

In order to precisely control the exposure durations of the annulus and Landolt C displays, it was necessary for a video switching unit to interface the two cameras with the stereogram generator. This unit controlled the amount of time a camera's video signals adressed the stereogram generator by counting the number of vertical scans (each vertical scan

frame lasted 16 msec). With the number of frames predetermined, the video switching unit thus controlled the exposure duration of the Landolt Cs and annuli (some multiple of 16 msec) and controlled the duration between stimulus onsets (also some multiple of 16 msec).

Stimuli

A Landolt C, which was the target, and an annulus, which was the mask, were the only stimuli employed in these experiments. The dimensions of these stimuli are shown in Fig. 2. The disparity and exposure duration of the target and mask were varied for different experiments and for different observers. The direction of the disparities was always crossed.

General Procedure

A four-choice forced-choice task was employed in all the masking experiments. The observer was instructed to judge the position of the gap of the Landolt C, which was located at 3, 6, 9, or 12 o'clock. The subject was asked to respond up, down, left, or right. A ready signal was given before the presentation of every trial. After every trial the subject was given feedback about the accuracy of the response. The position of the gap of the Landolt C was selected in a quasirandom fashion.

It was hoped that preexperimental training would be sufficient to eliminate the effects of learning prior to formal data collection. To that end, subjects received extensive practice detecting gap position. At the end of training each subject's performance seemed stable for a given exposure duration. Yet during the first three experiments there was a slight gain in performance, which was then corrected to the previous baseline by reducing exposure duration. After this correction there was no detectable practice effect--the relation between exposure duration and detectability was stable.

At the beginning of each experimental session subjects were presented with 10 to 25 warm-up trials. Each experimental session lasted approximately one hour. Between 12 and 18 blocks comprised a session, with each block containing 25 trials. After each block there was a short rest period.

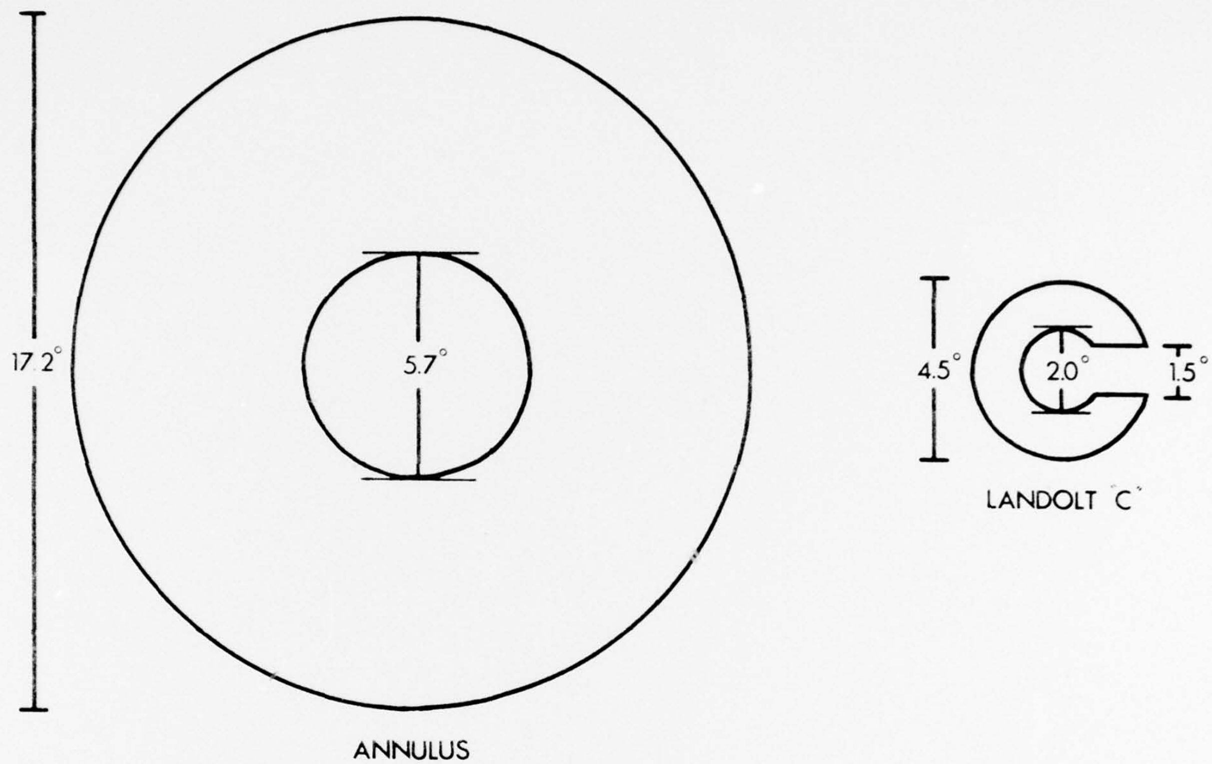

Fig. 2. Configuration and dimensions of the stimuli.

EXPERIMENTS

In this section the individual experiments are discussed. For each experiment, descriptions of stimuli and specific procedures are followed by presentation of the results. In all, there were nine experiments. To assist in the discussion of these experiments, they are divided into three conceptual categories.

The first category contains two experiments that measured the detectability of cyclopean forms. The purpose of these experiments was to obtain baseline data on the detectability of the cyclopean Landolt C.

The second category contains two experiments dealing with the visual masking of cyclopean contours. The purpose of these experiments was to estimate stimulus parameters for the cyclopean target and mask used in the depth separation experiments.

The third category contains five experiments dealing with the main topic, the effect of depth separation on visual masking. The purpose of these experiments was to examine the effect of depth separation when the mask was in front of or behind the target and when the mask was presented before, after, or simultaneously with the target.

Detectability of Cyclopean Forms (Experiments 1 and 2)

Experiment 1. Detection of a cyclopean Landolt C as a function of exposure duration. The purpose of this experiment was to measure sensitivity to a cyclopean target by measuring detection performance as a function of exposure duration. The obtained psychophysical functions relating detection performance and exposure duration were used to choose appropriate stimulus values in subsequent masking experiments. So, in this sense, the experiment was preliminary.

Stimulus. The target was a Landolt C whose dimensions were described in the previous section. It appeared to be located between the observer and the screen (disparity 36'38").

Specific procedure. Exposure duration was held constant for each block of 25 trials. Blocks representing exposure durations were presented in an orderly sequence, e.g., long duration to short duration, and were counterbalanced within a session, across sessions, and across observers. The range of exposure durations for each observer was selected to span chance performance, which was 25% correct, and near perfect performance, which was 100% correct. For subjects SWL and CVL, ten exposure durations were used; for subjects SLS and TSL, nine exposure durations were used. One hundred trials were run for each exposure duration.

Results. The functions relating per cent correct detections with exposure duration for the four subjects are plotted in Fig. 3. The effect of exposure duration was statistically significant ($F = 37.24$, $df\ 7/21$, $p < .001$).

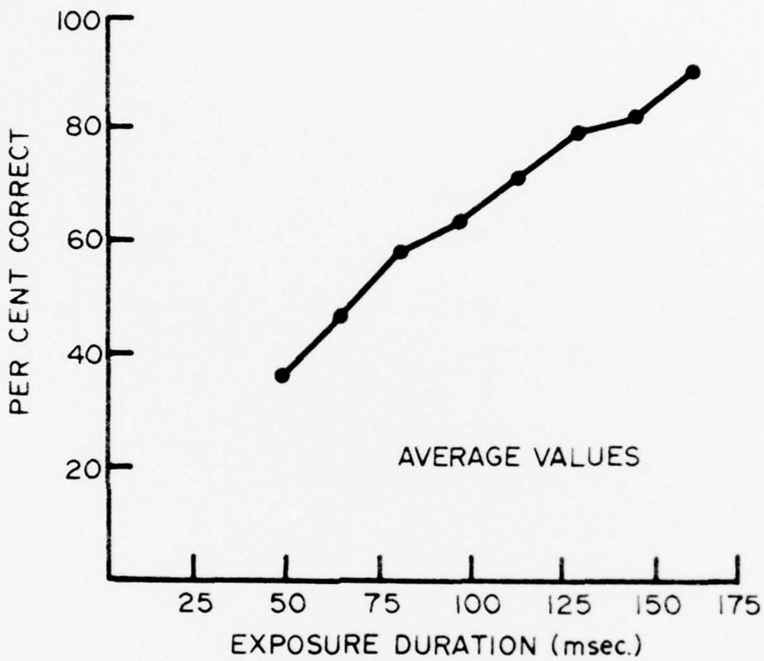

Fig. 3. Detectability of target as a function of exposure duration, averaged across observers (Experiment 1).

All subjects performed at chance levels when the exposure duration was below 48 msec; above 128 msec, all subjects reliably detected the gap of the Landolt C. The increase in performance as a function of exposure duration seems to be linear. If an arbitrary threshold were to be chosen halfway between perfect and chance performance, the duration threshold for detecting cyclopean Landolt Cs would be about 96 msec.

It is probable that the duration threshold for a Landolt C constructed from cyclopean contours is much longer than the duration threshold for a Landolt C constructed from physical contours (i.e., contours formed from a luminance discontinuity on the retina). To explore this possible difference, a brief experiment was conducted in which detectability was measured for a Landolt C composed of only those dots in the stereogram that were disparate. These dots, which formed a luminance discontinuity, comprised a Landolt C that had a configuration identical to the cyclopean Landolt C. In this experiment, all subjects correctly detected, without error, the position of the gap at the shortest available exposure duration, 16 msec.

Experiment 2. Detection of a cyclopean Landolt C as a function of exposure duration and binocular disparity. The purpose of this experiment was to measure sensitivity to a cyclopean target for different binocular disparities. The results of this experiment were used to choose disparity values in subsequent experiments.

Stimulus. The target was a Landolt C whose dimensions were described earlier. Seven target disparities were studied. The disparities ranged from 9'9", where the target appeared about 1 ft in front of the screen, to 64'3", where the target appeared about 6 ft in front of the screen. Four exposure durations were studied: 160, 128, 96, and 64 msec.

Specific procedure. Exposure duration and disparity were constant throughout a block of 25 trials. Exposure duration and disparity blocks were counterbalanced across sessions. Fifty trials (2 blocks) were run for each combination of exposure duration and disparity.

Results. The functions relating per cent correct detections with exposure duration and disparity are plotted for the four subjects in Fig. 4. There were main effects of exposure duration ($F = 25.53$, df 3/9, $p < .001$) and disparity ($F = 5.97$, df 6/18, $p < .002$), and there was a significant interaction between exposure duration and disparity ($F = 1.94$, df 18/54, $p < .032$).

Taken together, detection performance did not vary in a monotonic fashion with changes in depth. For shorter durations, there was an optimum depth position, corresponding to a disparity of 20-30', at which target detectability was enhanced. At the longer exposure duration of 160 msec the effect of depth on target detectability was diminished, and this lack of effect provided the basis for the significant interaction between exposure duration and disparity.

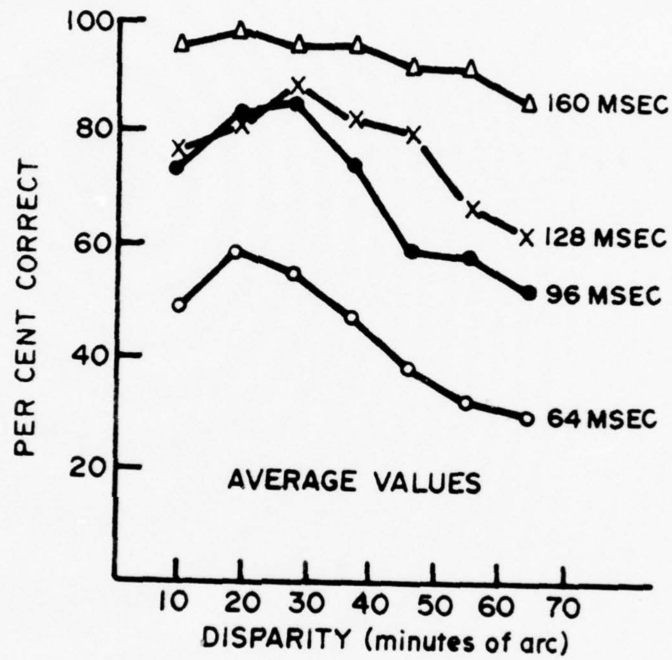

Fig. 4. Detectability of target as a function of disparity and exposure duration, averaged across observers (Experiment 2).

It is not surprising that a cyclopean target is more difficult to detect when its disparity is either large or small. A similar relation between disparity and sensitivity is also found with physical contours (see, for example, Foley, Applebaum, & Richards, 1975). This effect of disparity could be explained in the following way. For small disparities, a threshold would be approximated, which would lead to a decrease in detectability; for large disparities, a fusional limit would be exceeded, which would lead to a decrease in detectability.

Visual Masking with Cyclopean Stimuli (Experiments 3 and 4)

Experiment 3. The effect of lateral separation on visual masking with cyclopean contours. As discussed earlier, the distance between the edges of the target and mask is a highly effective variable in visual masking with physical contours. When the distance increases, the amount of masking increases. The purpose of this experiment was to determine if distance is an effective variable in masking with cyclopean contours. The information gathered from this experiment was used to select the characteristics of the mask in subsequent experiments.

Stimuli. Both the target and mask appeared to lie in the same depth plane. The disparity was 36'38". Three different annuli were used as masks. The outer diameter of the three annuli was $17^{\circ}12'$. The inner diameters were $5^{\circ}32'$, $9^{\circ}10'$, and $12^{\circ}59'$; therefore, the distances between the outer edge of the target and the inner edge of the mask were 1°, $4^{\circ}40'$, and $8^{\circ}30'$. The exposure duration of the mask was 160 msec. The exposure duration of the target was varied across observers. A duration was chosen so that the target, when presented alone, was identified correctly about 80% of the time. For subjects SWL and CVL, the target duration was 112 msec. For subject SLS, the target duration was 96 msec. For subject TSL, the target duration was 80 msec. The presentation of the target and mask was simultaneous.

Specific procedure. In this experiment there were four conditions, three annulus sizes and a target-alone condition. Annulus size was constant throughout a block of 25 trials. The conditions were presented in an orderly sequence (e.g., large separation to small separation) and were counter-balanced within a session, across sessions, and across subjects. One hundred trials were run in each of the four conditions.

Results. The functions relating per cent correct detections with the inner diameter of the annulus are plotted for the four subjects in Fig. 5. The dashed line in this figure denotes the level of performance when the target was presented alone. The effect of annulus size was significant ($F = 32.92$, df 2/6, $p < .001$).

For each subject, performance decreased as the inner edge of the annulus approached the outer edge of the target. In other words, the amount of masking increased as the separation between the target and mask decreased. When the separation between the edges was small, the amount of masking was substantial. For example, in the condition where the separation between

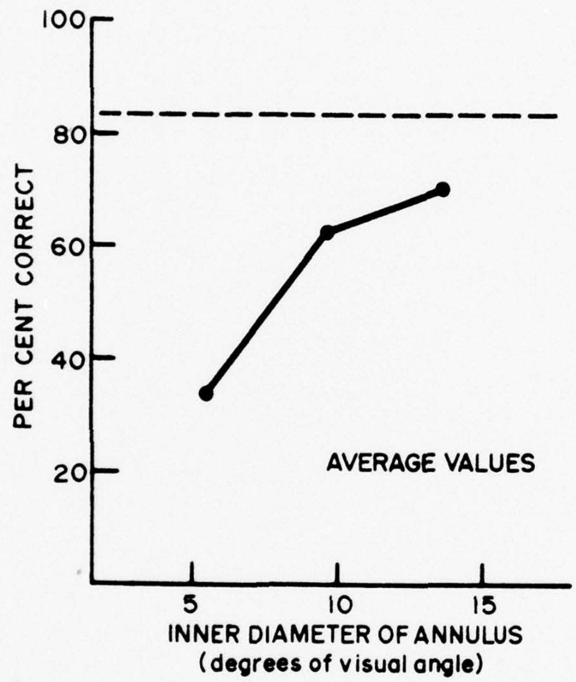

Fig. 5. Detectability of target as a function of the inner diameter of the mask, averaged across observers (Experiment 3).

edges was 1°, the average performance was about 50% of the performance when no mask was presented. However, even when the separation between the edges was $8^{\circ}30''$ (the greatest separation tested), detection performance was significantly lower than when no mask was presented ($t = 10.37$, df 3, $p < .01$).

It is of interest that the amount of lateral interaction between cyclopean targets and mask is measurable in degrees of visual angle. With physical contours the lateral interaction is less extensive, being measured in minutes of visual angle (Growney & Weisstein, 1972; Kolers, 1962).

Experiment 4. The effect of temporal separation on visual masking with cyclopean contours. In visual masking with physical contours, another effective variable is the duration between the onsets of the target and of the mask, which is referred to as stimulus onset asynchrony (SOA). As the mask and target are separated in time the amount of masking decreases. The purpose of this experiment was to examine the temporal aspects of visual masking with cyclopean contours. The data gathered in this experiment were used to choose SOA values in the depth separation experiments.

Stimuli. The target and mask appeared to lie in the same position in depth. The disparity was 36'38". The exposure duration of the mask was 160 msec. The exposure duration of the target was varied for individual observers so that the level of performance was 80% correct when no mask was presented. For subjects SWL, CVL, and TSL, the target duration was 80 msec; for subject SLS, the target duration was 64 msec. The time between target and mask presentations, measured from stimulus onsets, was some multiple of 16 msec, the frame rate of the display.

Results. The function relating per cent correct detections with SOA is plotted for the four subjects in Fig. 6. The dashed line in this figure denotes the level of performance when no mask was presented. The effect of SOA was significant ($F = 3.87$, df 29/87, $p < .001$).

When the target preceded the mask (i.e., backward masking), there was a monotonic increase in detectability as a function of temporal separation. At a separation of 100 msec, the mask had little influence on the detectability of the target. This effect of temporal separation is not unlike the backward masking effects revealed with physical contours (see, for example, Schiller & Smith, 1965).

However, when the mask preceded the target (i.e., forward masking), the effect of temporal separation was different. On the average, detectability was lower than baseline (i.e., the target-alone condition) across a broad range of temporal separations extending more than 300 msec. With physical contours, forward masking usually occurs across a much smaller range except for the condition where mask luminance greatly exceeds target luminance (Weisstein, 1972).

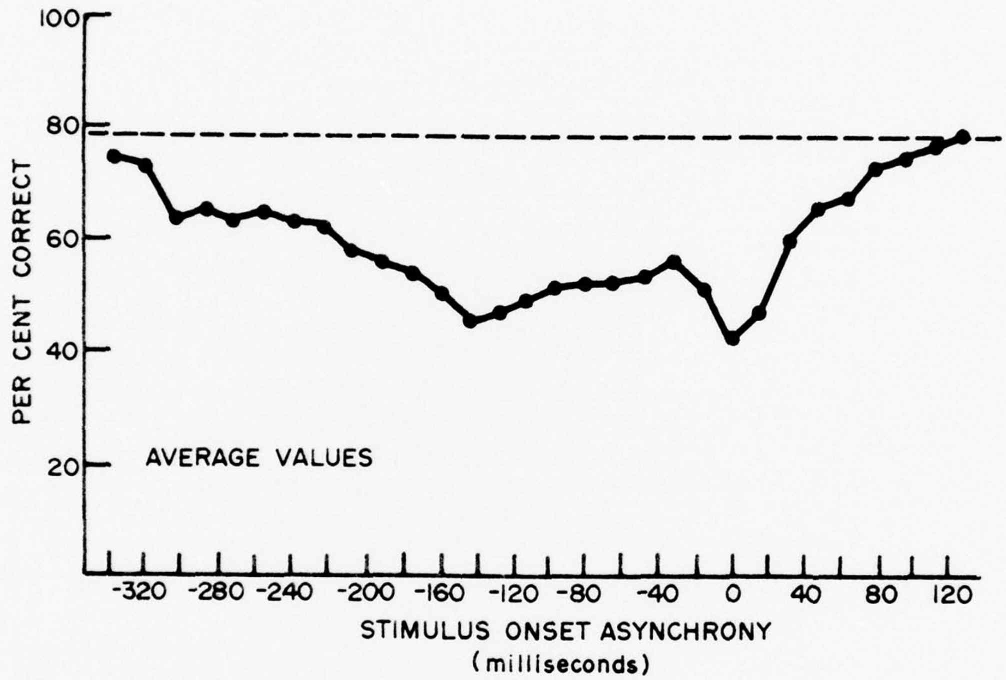

Fig. 6. Detectability of target as a function of stimulus onset asynchrony, averaged across observers (Experiment 4).

Depth Separation and Visual Masking (Experiments 5 through 9)

Experiment 5. The effect of depth separation on visual masking with cyclopean contours. In Experiments 3 and 4 two variables already extensively examined in relation to visual masking were reexamined in the context of cyclopean contours. In the next series of experiments a new variable, perceived depth, was studied.

In this experiment, the magnitude of masking was measured while variations were made in the relative depths of the target and mask. As discussed in the introduction, this experiment provides a test of the adequacy of masking models based upon lateral inhibition. Furthermore, this experiment tests the hypothesis that depth analysis precedes contour analysis, with the outcome supporting the view offered either by the global theories or by the specific-cue theories of depth perception.

Stimuli. The target's position in depth was closer to the observer than in prior experiments (disparity 64'3"). The target duration was 80 msec for subjects SWL, CVL, and TSL; for subject SLS the duration was 64 msec. The position of the mask was located either in the same depth plane as the target or at one of six positions located behind the target. The disparities of the mask ranged from 9'9" to 64'3" in 9'9" steps. The exposure duration of the mask was 160 msec. The target and mask were presented simultaneously (SOA = 0).

Specific procedure. Target detectability was measured for each of the seven positions of the mask in depth and for a condition in which no mask was presented. Mask disparity was constant throughout a block of 25 trials. The conditions were presented in an orderly sequence (e.g., target and mask in the same depth plane to the mask far behind the target) and were counterbalanced within a session, across sessions, and across observers. One hundred trials were run for each condition.

Results. The function relating per cent correct detections with depth separation for the four subjects is plotted in Fig. 7. The dashed line in this figure denotes the level of performance when the target was presented alone. The effect of depth separation was significant ($F = 52.15$, df 6/8, $p < .001$).

The variable of depth separation, heretofore not examined, was shown in this experiment to contribute significantly to the amount of masking; as the target and mask were separated in depth, the amount of masking decreased. This effect was reliable across all observers and, moreover, it was monotonic. The variable of depth separation was as effective as other, more traditional variables such as temporal separation and lateral separation.

Experiment 6. The effects of depth separation and SOA on visual masking with cyclopean contours. In the last experiment the target and mask were presented simultaneously and the mask appeared either at the same depth as the target or at one of several positions located behind the target. In this experiment temporal and depth separation were studied in factorial combination.

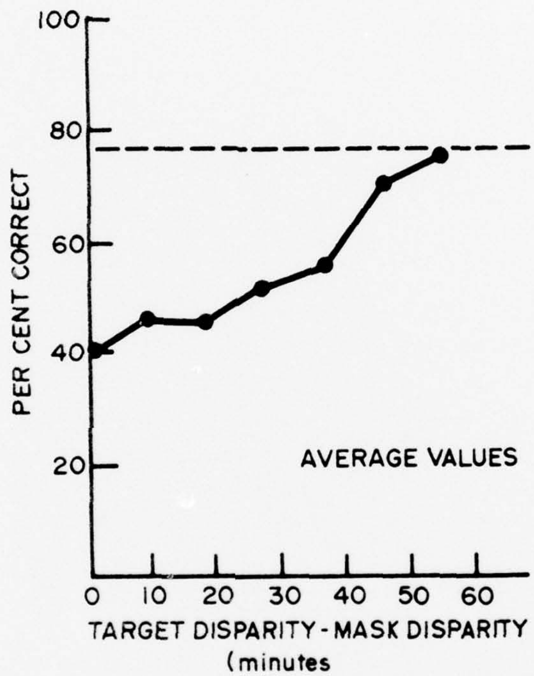

Fig. 7. Detectability of target as a function of the separation in depth of the target and mask, averaged across observers (Experiment 5).

The mask was presented before, after, or simultaneously with target presentation and appeared at the same depth, behind, or in front of the target. The purpose of this experiment was twofold: To determine if the effect of depth separation remained constant across different temporal separations, which were shown in Experiment 5 to significantly influence the amount of masking, and to determine if the effect of depth separation was also effective when the mask was in front of the target. Recall that in the previous experiment the mask was always behind the target.

Stimuli. The target appeared about midway between the observer and the screen (disparity 36'38"). The target durations were 80 msec for subjects SWL, CVL, and TSL, and 64 msec for subject SLS. The mask appeared behind the target (disparities 9'9", 18'20", or 27'29"), in front of the target (disparities 45'48", 54'58", or $1^{o}4'3"$), or in the same depth plane as the target (disparity 36'38"). The target and mask were presented simultaneously (SOA 0 msec), the mask was presented 32 msec after the target (SOA 32 msec), or the mask was presented 128 msec before the target (SOA -128 msec).

Specific procedure. Target detectability was measured for each combination of mask disparity and SOA value. Target detectability was also measured when no mask was presented. Mask disparity and SOA were constant throughout a block of 25 trials. For each SOA the conditions were presented in an orderly sequence (e.g., mask in front of target to mask behind the target) and were counterbalanced within a session, across sessions, and across observers. One hundred trials were run for each combination of mask disparity and SOA. In the target-alone condition 300 trials were run, 100 for each SOA value.

Results. The functions relating per cent correct detections with depth separation and SOA for the four subjects are plotted in Fig. 8. The dashed line in this figure denotes the level of performance when the target was presented alone. There was a significant main effect for depth separation ($F = 17.60$, df 6/8, $p < .001$), a marginally significant main effect for SOA ($F = 4.202$, df 2/6, $p < .072$), and a significant interaction between these variables ($F = 2.32$, df 12/36, $p < .025$).

In this experiment there were two interesting results concerning the effect of depth separation on visual masking. First, it was shown that the effect of depth separation was not constant across temporal separation. This was confirmed statistically by the presence of an interaction between SOA and depth separation. The functions obtained when SOA was 32 msec and zero were similar, but these functions differed from the function obtained when SOA was -128.

Second, it was shown that the effect of depth separation when the mask was located behind the target was different from the effect when the mask was located in front of the target. As had been found in Experiment 5, when the mask was behind the target the masking effect diminished as the target and mask were separated in depth for all values of SOA. But when the mask was in front of the target the masking effect was undiminished and even enhanced for the case in which the mask was presented 128 msec before the target.

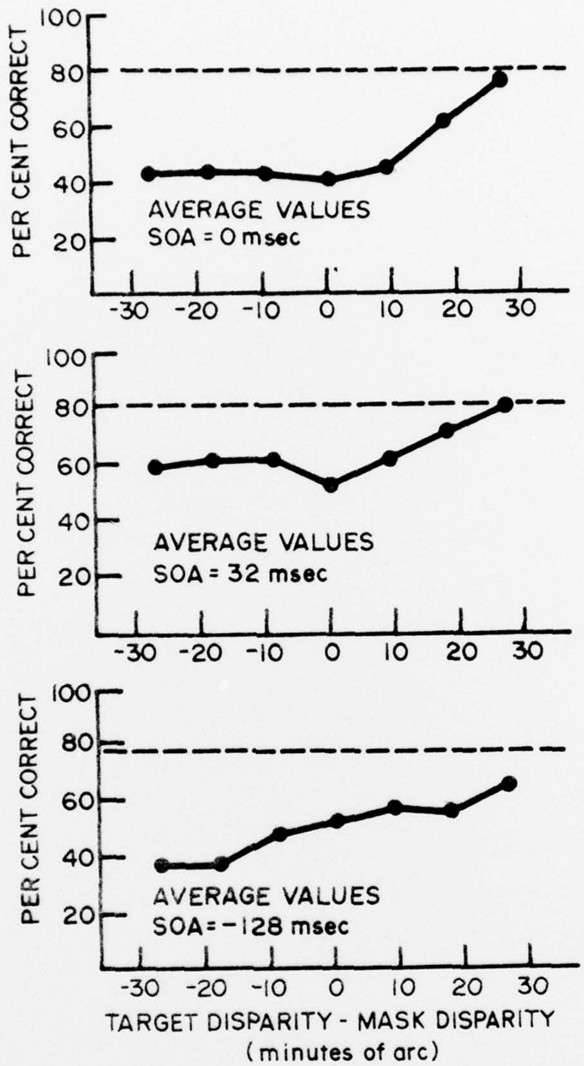

Fig. 8. Detectability of target as a function of depth separation and stimulus onset asynchrony, averaged across observers (Experiment 6).

Experiment 7. The perception of relative depth of cyclopean targets and masks. The interpretation of the results of previous experiments has implicitly included the assumption that the perceived depth of the target and mask was the critical variable controlling masking. To substantiate that assumption, it is necessary to verify that differences in disparity did induce differences in perceived depth. For long exposure durations this relation between disparity and perceived depth is evident; yet for brief exposure durations, like those used in the preceding experiments, this relation is not so obvious. Accordingly, in this experiment depth separation thresholds were measured for two SOA values, when the target and mask were presented simultaneously (SOA zero) and when the mask was presented 128 msec before the target (SOA -128 msec).

Stimuli. The target was located at a middle depth position (disparity 36'38"). The target durations were 80 msec for SWL, CVL, and TSL, and 64 msec for SLS. The position of the mask was varied employing the seven disparity values used in Experiment 6. The exposure duration of the mask was 160 msec. The SOA values were either 0 or -128 msec.

Specific procedure. The observer's task was to judge whether the mask was in front of or behind the target (the observer was permitted only these two alternatives). Either a "front" or a "back" response was considered correct when the disparity of the target and mask was the same. Feedback was provided after each response. For each SOA value there were eight blocks of 21 trials, in which mask disparity was replicated three times. In the last block there were only seven trials in which there was one replication of each mask disparity. Therefore, across all blocks there were 25 trials run for each combination of mask disparity and SOA. The order of presentation within each block was randomized. The order of presentation of SOA values was counterbalanced across the four observers.

Results. The psychometric functions relating the proportion of "front" responses with disparity and SOA for the four observers are plotted in Fig. 9. There was a main effect for disparity ($F = 71.98$, df 6/8, $p < .001$). There was neither a main effect for SOA ($p > .10$) nor an interaction between SOA and disparity ($F < 1.0$). Using the normal graphic process (see Guilford, 1954), the estimated difference thresholds were 9'16" for the 0-msec SOA condition and 8'35" for the -128-msec SOA condition.

This experiment demonstrated that an observer can discriminate the relative depths of briefly presented cyclopean targets and masks, and provided support for the claim that perceived depth influenced the amount of masking in Experiments 5 and 6.

Experiment 8. The change in perceived size as a function of disparity of the cyclopean mask. Throughout the previous experiments, even though the physical size of the annulus was constant, its perceived size varied with changes in disparity; it grew larger when it moved away from the observer and it grew smaller when it moved toward the observer. This relationship between perceived size and perceived distance due to binocular disparity was recognized by Wheatstone in his early work with the stereoscope, and it has

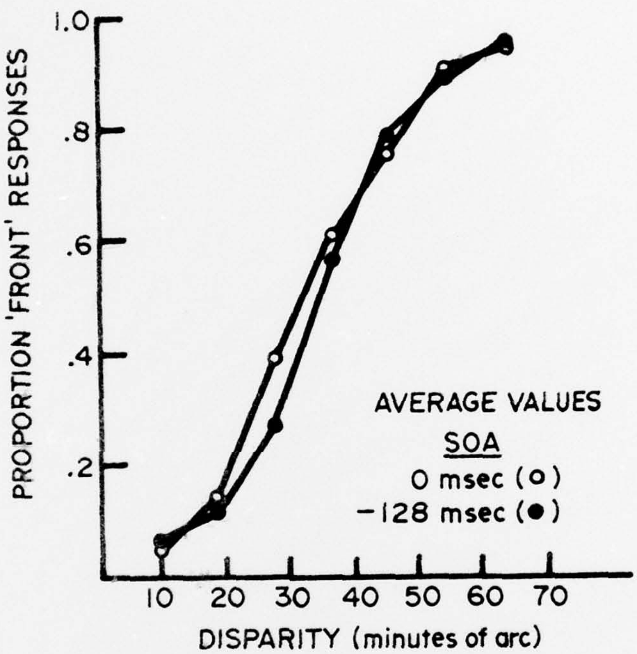

Fig. 9. Proportion of "front" responses as a function of disparity of the mask, averaged across observers (Experiment 7).

been studied more extensively in this century by Gulick and Lawson (1976). The purpose of this experiment was to measure the nature of this change using dynamic random-element stereograms, a stereoscopic display whose size-distance relationships have not been studied.

It should be pointed out that the introduction of disparity in the present random-element stereograms does not alter the binocular correlation between corresponding left-eye and right-eye elements in the submatrix. In the present display all the elements of the submatrix are shifted by the same amount so that the binocular correlation between corresponding elements of the submatrix remains 1.0 across all disparities. Because disparities are generated in this fashion, the present random-element stereograms are suitable for the purpose of measuring size-distance relationships. In other types of random-element stereograms not all the elements of the submatrix are shifted a constant amount. One outcome of those methods of generating disparities is that binocular correlation decreases as disparity increases (Bridgman, 1964). Because of that relationahip those types of random-element stereograms would not be suitable for the purpose of measuring size-distance relationships (see Gulick & Lawson, 1976).

Stimuli. In this experiment the stimuli were two annuli--the standard annulus, which was identical to the one used in the previous experiments (inner diameter 15 in), and the comparison annulus, whose size could be continuously varied by means of a zoom lens controlled by the observer. The standard annulus was located at a middle depth position (disparity 36'38"). The position of the comparison annulus was in front (disparity 45'48", 54'58", or $1^{o}4'3''$), behind the target (disparity 9'9", 18'20", or 27'29"), or in the same depth plane as the target (disparity 36'38"). The two annuli were alternately presented at the rate of 1 Hz.

Specific procedure. The observer's task was to adjust the inner diameter of the comparison annulus until its size appeared equal to the inner diameter of the standard annulus. The adjusted size of the inner diameter was measured. Each observer made three adjustments at each disparity level. After each adjustment was made the size of the comparison annulus was changed in a random fashion. The order of presentation of disparity levels was counterbalanced across subjects.

Results. The functions relating adjusted size and disparity are plotted for the four observers in Fig. 10. The effect of disparity on perceived size was statistically significant ($F = 67.49$, df 6/8, $p < .001$).

For each observer there was a linear increase in adjusted size with increasing levels of disparity, which means that the annulus grew smaller as it moved toward the observer. The Pearson product-moment correlation between average adjusted size and disparity was .99. The average extent of the change in size was 4 in or $1^{o}32''$ across the range of disparities. A regression line was fitted to the average values. Its slope was 0.06, which suggests that the size of the annulus changes 0.06 in for every minute of disparity.

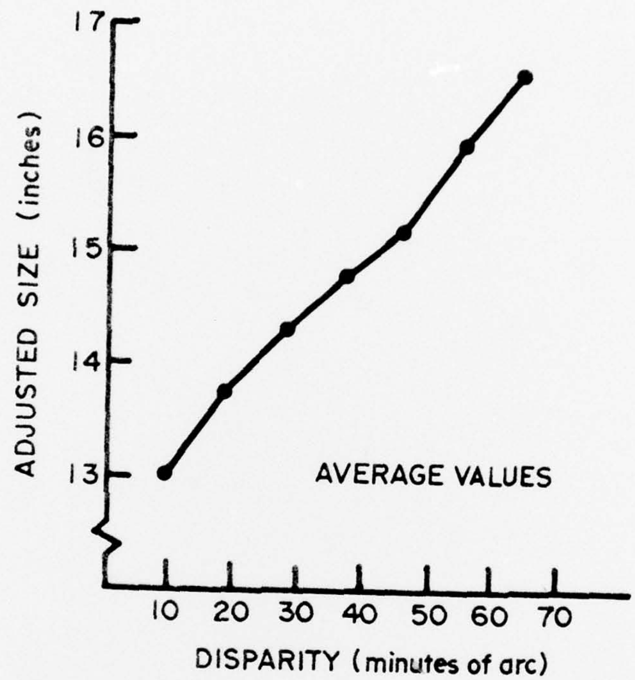

Fig. 10. Adjusted size of the inner diameter of the comparison annulus as a function of disparity, averaged across observers (Experiment 8).

Experiment 9. The effect of depth separation on visual masking with cyclopean contours correcting for changes in perceived size. The purpose of this experiment was to replicate Experiment 6 when the perceived size of the mask remained constant at all depth positions. The change in perceived size as a function of perceived depth, which was demonstrated in Experiment 8, provides some basis for interpreting the characteristics of the masking functions obtained in Experiment 6. In Experiment 8 it was found that, under the condition of simultaneous presentation, a mask that appeared in front of the target interfered more with target detectability than did a mask that appeared behind the target. This asymmetrical effect of the mask could be explained by the differences in perceived size produced by differences in perceived depth. When the mask was in front of the target, the mask appeared smaller and the apparent lateral distance between the edges of the target and mask decreased. When the mask was behind the target, the mask appeared larger and the apparent lateral distance between the edges of the target and mask increased. If perceived lateral separation, like physical lateral separation, is effective in determining the amount of masking, then the decrease in lateral separation that occurs when the mask is closer would produce more masking and, as a corollary, the increase in lateral separation that occurs when the mask is further away would produce less masking. According to this explanation, if perceived size of the mask was kept constant across positions in depth, which would control for changes in apparent lateral separation, one should obtain a symmetrical effect of the mask at near and far locations.

Also recall from Experiment 6 that when SOA was -128 msec the amount of masking was greater when the mask was in front of the target than when the target and mask were in the same depth plane; that is, there was an increase in the amount of masking as a function of the perceived depth of the mask. This effect could also be explained by differences in perceived size. As the mask progresses through several depth positions, beginning behind the target and ending in front of the target, its perceived size grows smaller and the lateral distance between the edges of the target and mask decreases. Because of the differences in lateral distance, it would be expected that the amount of masking would increase as the position of the mask in depth is closer to the observer. Note that this explanation is not based upon the relative depths of the target and mask; rather, it accounts for the observed result solely in terms of differences in perceived size. According to this explanation, if perceived size were kept constant across changes in perceived depth, one should find no effect of depth separation when the mask is presented first.

Stimuli. The disparity, SOA, and exposure duration of the target and the mask were the same as in Experiment 6. The size of the mask was varied across levels of disparity for individual observers. The size of the mask was adjusted to match the average setting for a disparity made by the observer in Experiment 8.

Specific procedure. Target detectability was measured for each of the seven positions of the mask in depth and for a condition in which no mask was presented. Mask disparity and SOA were constant throughout a block of 25 trials. The conditions were presented in the same manner as in

Experiment 6. One hundred trials were run for each combination of SOA and mask disparity and 200 trials were run for the target-alone condition.

Results. The functions relating per cent correct detections with depth separation and SOA using the corrected annulus sizes are plotted for the four observers in Fig. 11. The dashed line in this figure denotes the level of performance when no mask was presented. The data for each SOA value were analyzed separately. For an SOA of 0 msec, there was a main effect for depth separation ($F = 9.76$, df 6/18, $p < .001$). For an SOA of -128 msec, there was also a main effect for depth separation ($F = 3.78$, df 6/18, $p < .013$).

In Fig. 12 are plotted the average values obtained in this experiment and in Experiment 6. These figures portray the effect of correcting for changes in the perceived size of the mask. The data were analyzed separately for each SOA value. For an SOA of 0 msec, there was a marginal effect of size adjustment ($F = 6.84$, df 1/3, $p < .078$) and a main effect of depth separation ($F = 13.64$, df 6/18, $p < .001$). There was no interaction between these variables. In a post hoc analysis, using Duncan's multiple range test, an effect of size adjustment was found for only the -20-min depth separation. For an SOA of -128 msec, there was only a main effect of depth separation ($F = 12.49$, df 6/18, $p < .001$).

In summary, correcting for changes in perceived size had little effect on the asymmetry of the effect of depth separation. An effect of size adjustment was found for only one depth separation when the target and mask were presented simultaneously. In other words, perceived lateral separation had little influence when the target and mask occupied different depth planes.

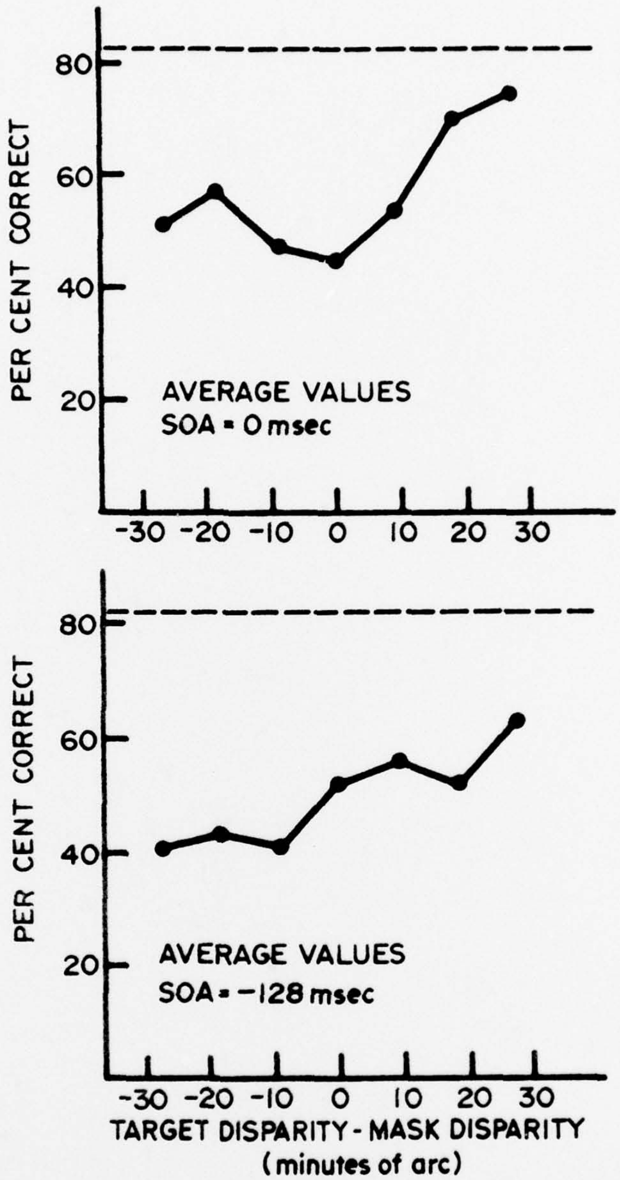

Fig. 11. Detectability of target as a function of depth separation and stimulus onset asynchrony using corrected annulus sizes, averaged across observers (Experiment 9).

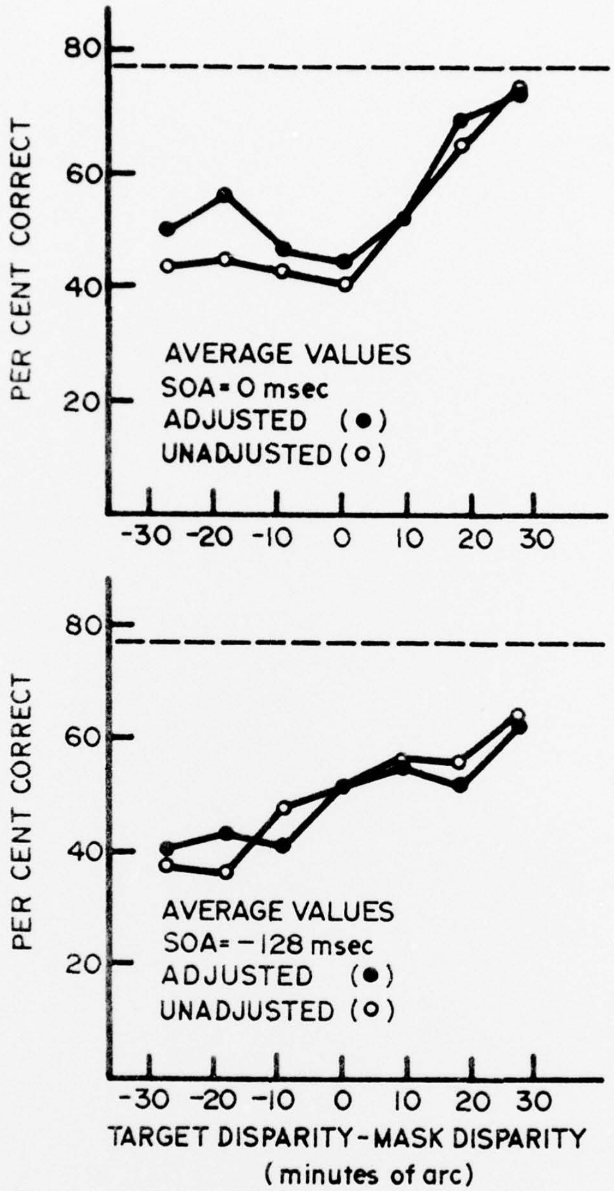

Fig. 12. Depth-separation masking functions (SOA = 0 and -128 msec) for adjusted and unadjusted sizes of annulus, averaged across observers.

DISCUSSION

In this section, the results of specific experiments are considered with respect to the primary objectives of the inquiry. Several experiments dealt with methodological issues because there has been virtually no prior research on metacontrast masking with stereoscopic contours formed from random-element stereograms. It was necessary, then, to establish that it was feasible to investigate masking with stereoscopic forms. Masking is a phenomenon that, by definition, requires briefly exposed transient stimuli, and it was important to establish that appropriate responses could be obtained to briefly exposed stereoscopic forms. The 50 to 70-msec range of exposure durations required for above-threshold recognition performance of the test stimulus (found in Experiment 1) is brief enough to preclude eye movements and it falls within the range of durations obtained with physical-contour stimuli tachistoscopically exposed. The similarity between stereoscopic-contour and physical-contour masking also extends to other variables and stimulus conditions. Masking declines as the spatial separation between test and mask edges increases (Experiment 3), a relationship found in physical-contour masking. In pilot work not reported in the paper, it was observed that masking required configurational similarity between test and mask stimuli, a requirement also necessary for physical-contour masking. The magnitude of masking under baseline conditions (i.e., SOA = 0 and both stimuli occupying the same depth plane) is of the same order of magnitude as that found in physical-contour masking. The relationship between masking and the temporal separation of test and mask within the backward masking paradigm (Experiment 4) matches that found in many experiments on physical-contour masking. The many similarities between stereoscopic and physical-contour masking suggest that the same processes underlie both phenomena, and serve to support the conjecture that the results obtained with stereoscopic contours can be generalized to the physical-contour case.

A clear difference between stereoscopic and physical-contour masking, however, did arise in that portion of Experiment 4 dealing with the forward masking paradigm. Forward masking extended for a considerable duration, on the order of 300 msec; such a result is not found in physical-contour metacontrast masking when the stimuli are of moderate intensity. Strong forward masking effects are found with physical stimuli only if the energy level of the mask greatly exceeds that of the test--in that situation, the most reasonable interpretation is that the mask has modified the adaptation level of the eye. In support of that interpretation, little or no forward masking is found under dichoptic stimulation conditions in which mask and target stimulate separate eyes. A retinal adaptation explanation, however, cannot explain the enduring forward masking found with stereoscopic contours. This is a unique result, whose implications will be discussed shortly.

With respect to the primary question motivating this research, concerning the role of depth separation of test and mask upon masking magnitude, it is clear from the results of Experiment 5 that depth separation exerts a significant influence. When the position in depth of the test remains fixed in space and the mask is displaced in depth from the test, such that the

mask appears farther away from the observer than does the test, masking declines with increasing depth separation. This result clearly supports relational theory over specific-feature theory, and it is an outcome difficult to accommodate within models of visual masking based on the concept of lateral inhibition.

But the interpretation becomes more complicated with the results of Experiment 6, which combined differences in temporal onset with differences in the depth positions of test and mask relative to their proximity to the observer. When the test was closer to the observer than was the mask, increasing depth separation reduced the magnitude of masking; but when the mask was closer to the observer than the test, masking magnitude did not abate and was even enhanced when the mask was temporally prior to the test, i.e., when the SOA values were negative. The asymmetry in masking duration and magnitude as a function of whether the mask or the test stimulus was closer to the observer is a surprising result. It is not likely that it could be attributed to changes in perceived size as a function of depth differences, as the results of Experiments 8 and 9 demonstrate. And, the results of Experiment 7 show that information about the relative depth positions of test and mask is retained at brief exposure durations. An hypothesis based upon some kind of differential eye movements is not tenable since many of the SOA values used in Experiment 6 were too short to permit eye movements to occur. Still another possibility is that the clarity of the mask varied as a function of depth position. But at exposure durations of 160 msec the mask was well above threshold and clearly visible at all depth positions. Perhaps the most reasonable conjecture is that the stimulus, either test or mask, that appears closer to the observer in visual space receives some special kind of high-priority processing by the visual system. This proposed bias, which might be termed the "front effect", may also extend to the temporal domain--a stimulus that appears first in the visual field would also receive similar priority. This "first effect" would account for the extended forward masking seen in Experiment 4.

Although a bias for the first stimulus or the front stimulus has not been observed previously, at least within the laboratory, it may not be an implausible or uncommon phenomenon. In the natural world, the stimulus that is either in front of another or occurs before another is the one whose view is unobscured by a second stimulus interposed between it and the observer. Such stimuli are typically seen in the center of the visual field, attract attention, and demand some response from the observer. The stimulus that is in front typically is the one that is closer, and it would be adaptive if the perceptual system did evolve some natural positive bias for processing these potentially important stimuli. Given that bias, together with the limitations on channel capacity assumed by most models of attention, it seems reasonable to suppose that the enhanced processing given the front or first stimulus would lead to some degradation of the subsequent stimuli following closely in space and in time. If further research establishes the generality of the front/first effect, it may place an important qualification on the information that can be portrayed in three-dimensional displays.

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